Progress in the science and technology of direct drive laser fusion with the KrF laser

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Work by the NRL laser fusion research team

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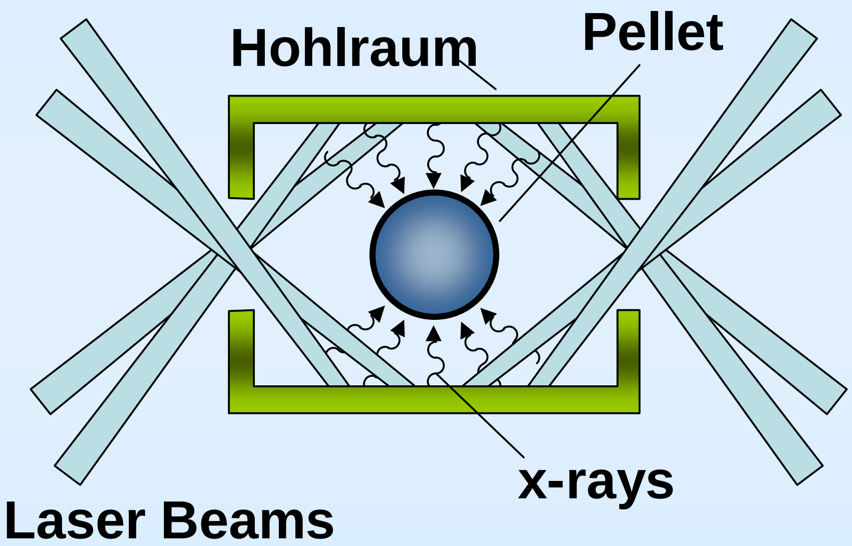
Opening remarks on path towards Inertial Fusion Energy (IFE)

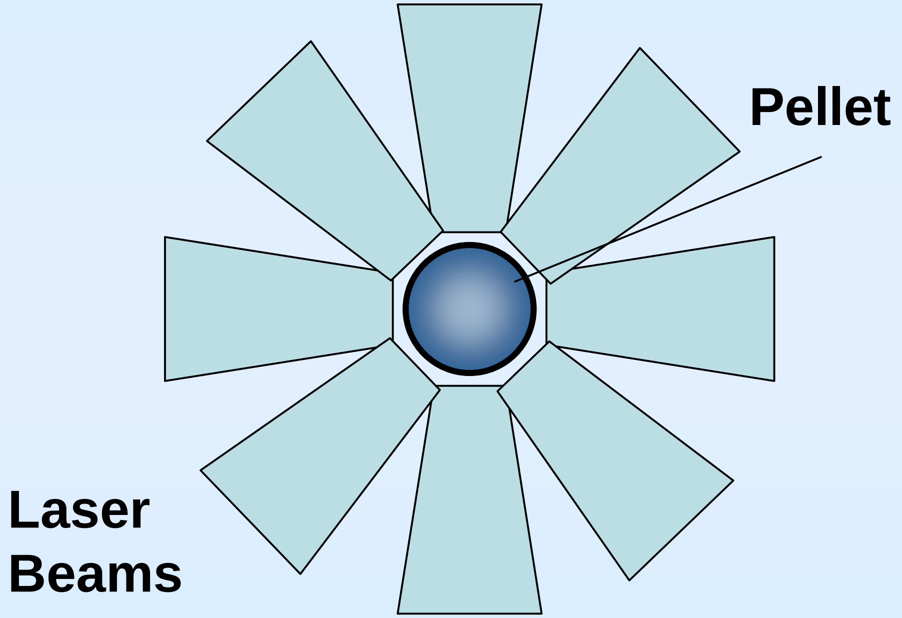
- Community needs to work together to provide the technical case for funding an IFE program.
- IFE program should nurture competition, with judgments made on the basis of technical progress and the potential of the various approaches to IFE.
- Direct-drive with lasers looks very attractive for IFE, the physics and needed technologies are mature and advancing.
- KrF provides physics advantages for direct drive.
- KrF's demonstrated performance is competitive with solid state lasers as a high-rep-rate durable, efficient IFE driver. (on several important parameters KrF technology leads)

Direct Laser Drive is a better choice for Energy

Indirect Drive (initial path for NIF)



Direct Drive (IFE)



- ID Ignition being explored on NIF
- Providing high enough gain for pure fusion energy is challenging.

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- DD Ignition physics can be explored on NIF.
- More efficient use of laser light, and greater flexibility in applying drive provides potential for much higher gains.

KrF light helps Direct Drive target physics (1)

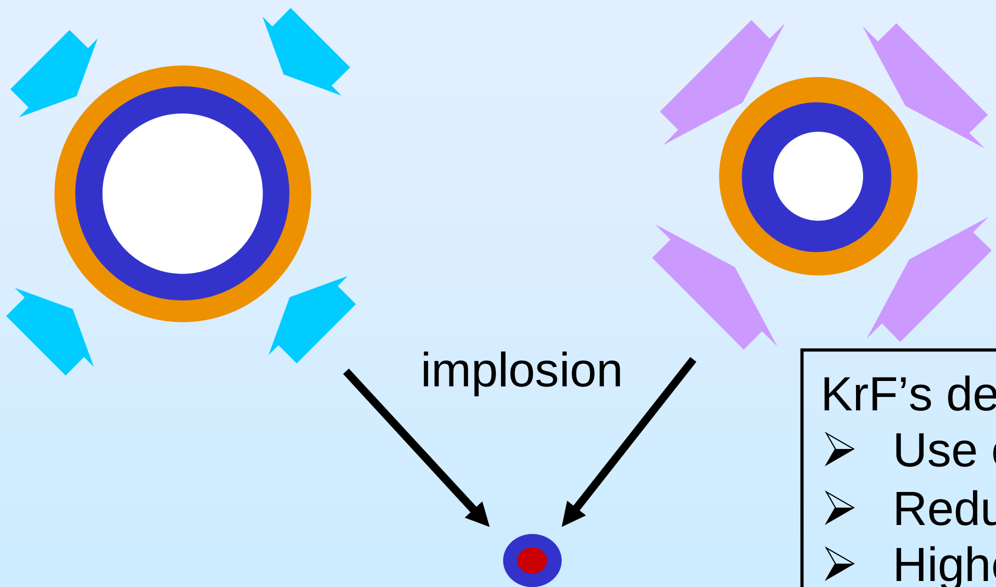
Provides the deepest UV light of all ICF lasers (λ=248 nm)

Deeper UV →

- Higher thresholds for laser-plasma instability
- Higher mass ablation rates and pressure
- Higher hydrodynamic efficiency
- Higher absorption fraction

351 nm laser (e.g. NIF)
lower drive pressure

KrF
higher drive pressure

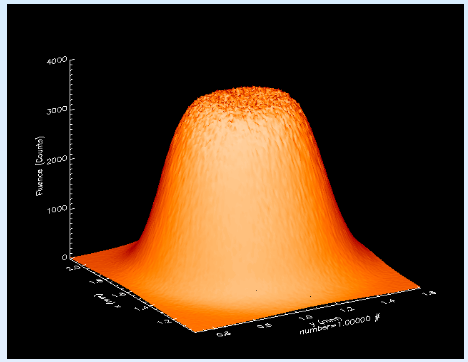


KrF's deep UV allows:

- Use of lower aspect ratio targets
- Reduced growth of hydro-instability
- Higher energy gain
- Use of less laser energy

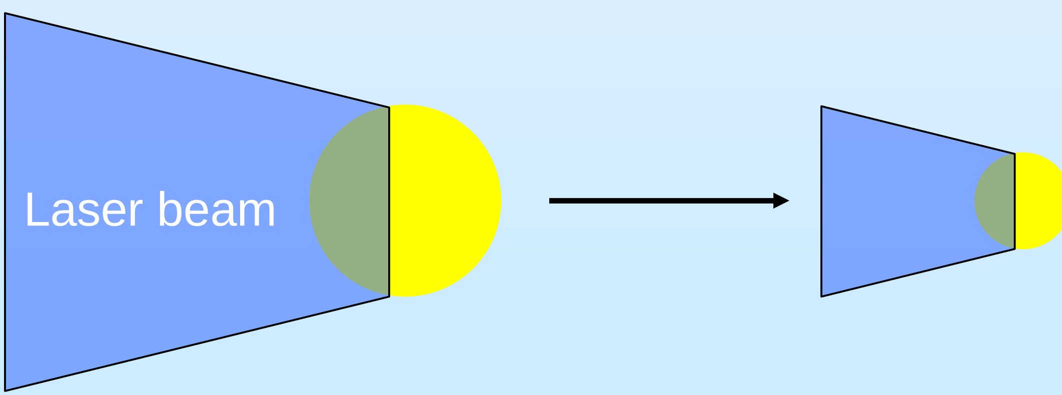
KrF Light helps the target physics (2)

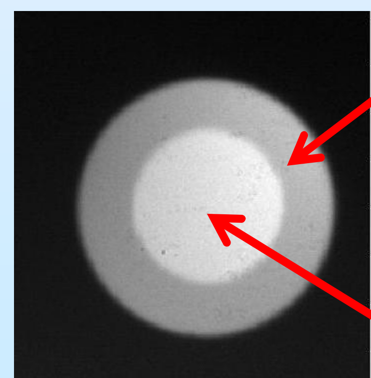
- KrF has most uniform target illumination of all ICF lasers.
  - **Reduces seed for hydrodynamic instability**



Actual Nike KrF focal profile

- KrF focal profile can zoom to "follow" an imploding pellet.
  - **More laser absorbed, reduces required energy by 30%**





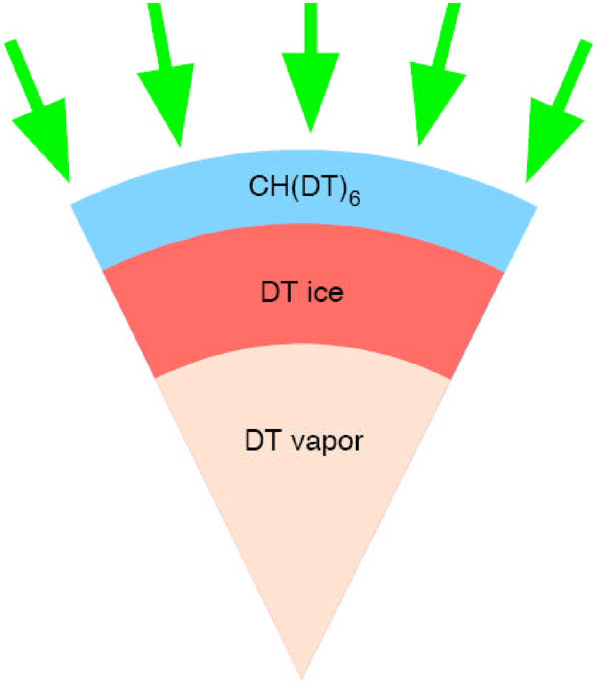
Early time

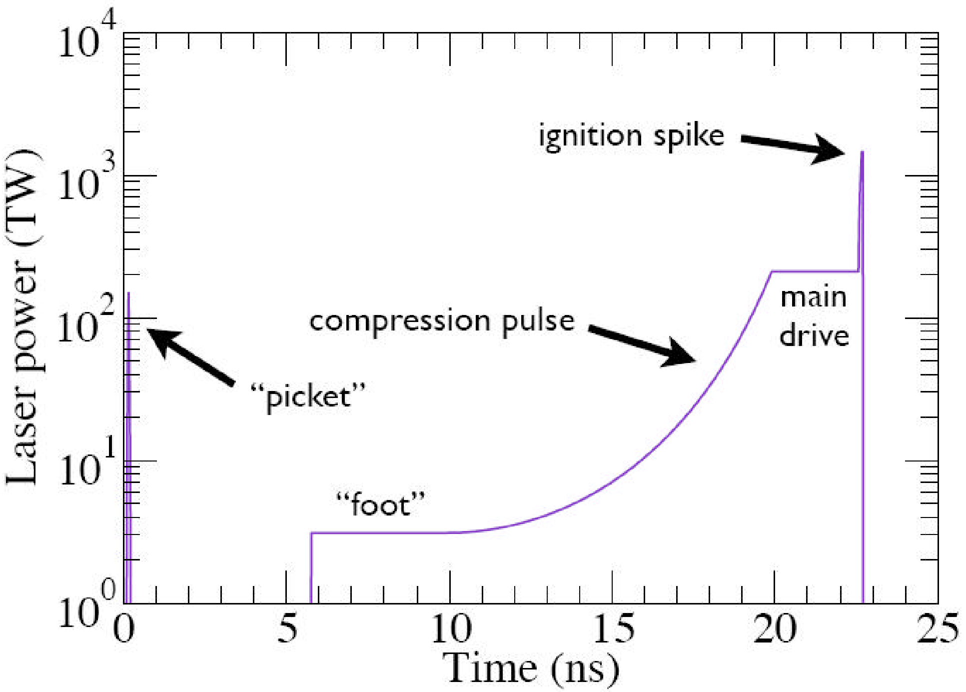
Nike zoomed focus

Late time

Shock Ignited (SI) direct drive targets*

Pellet shell is accelerated to sub-ignition velocity (<300 km/sec), and ignited by a converging shock produced by high intensity spike in the laser pulse.





Low aspect ratio pellet helps mitigate hydro instability

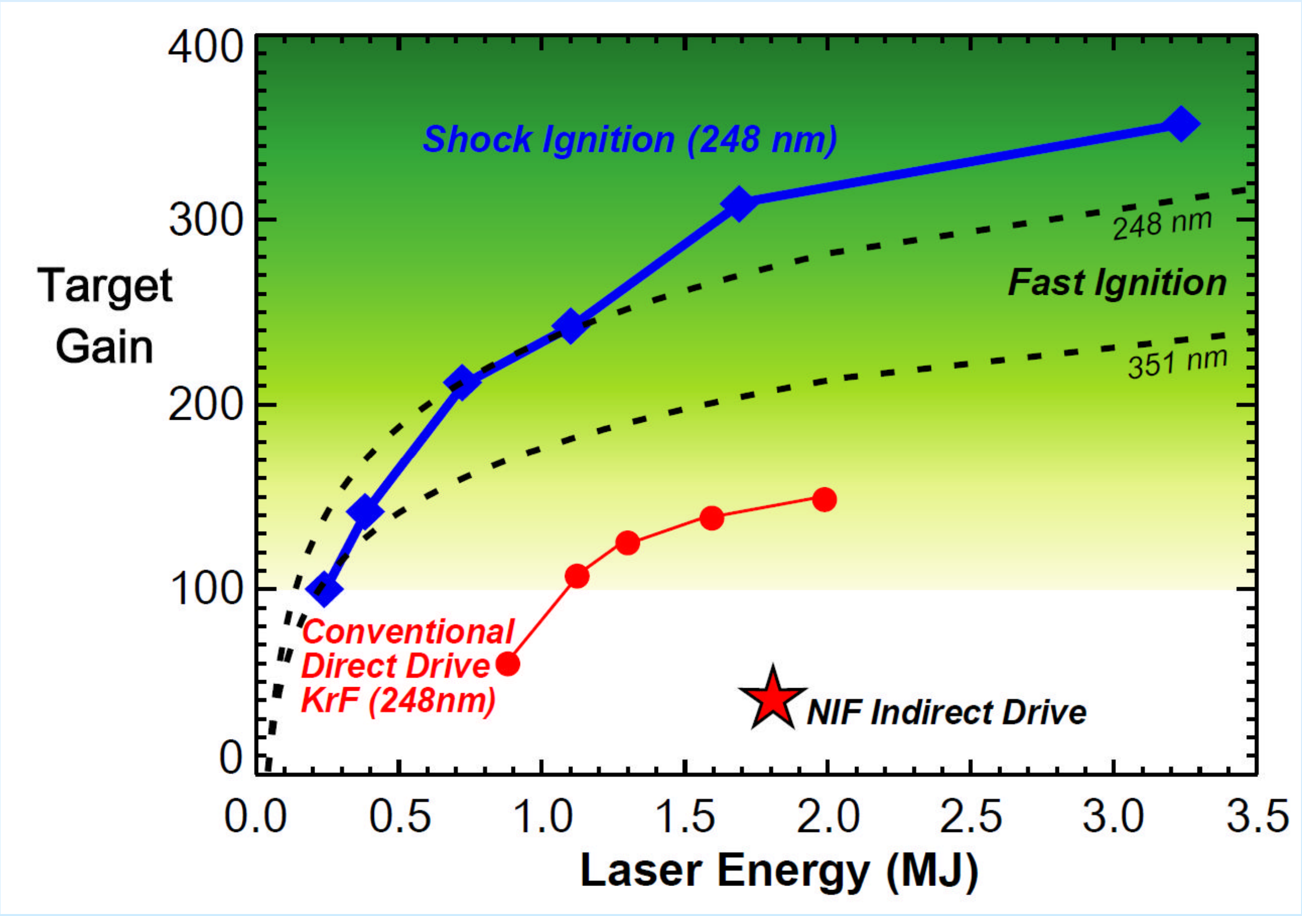
Peak main drive is 1 to 2 × 10^{15} W/cm^2

Igniter pulse is ~10^{16} W/cm^2

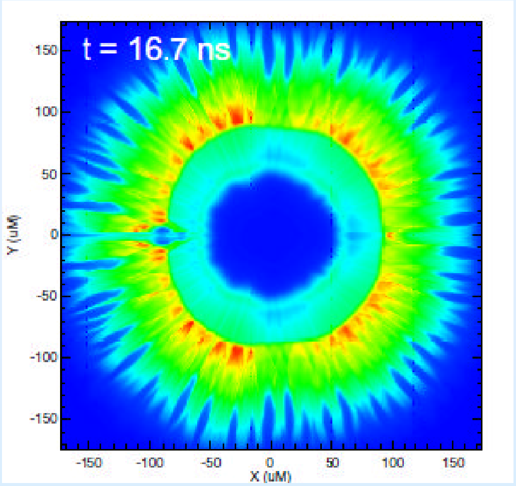
* *R. Betti et al., Phys.Rev.Lett.* ***98****, 155001 (2007)*

Simulations show very high gains with KrF driven shock ignition – similar to those predicted for Fast Ignition.

Peak gains from1-D simulations

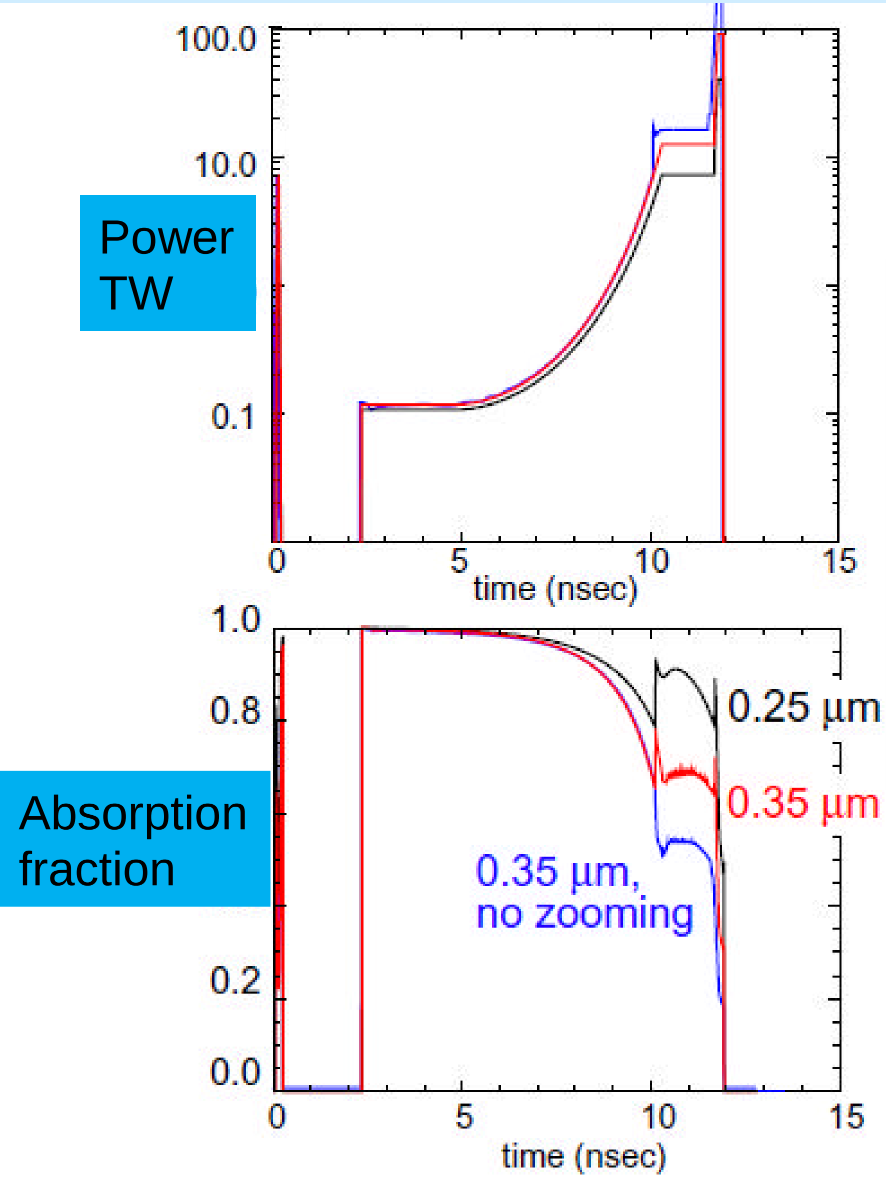


High resolution 2-D simulations
Gain = 102 @ 521 kJ



2D simulations typically give ~70% of the 1D gains

Shock ignition benefits from shorter λ and zooming



	KrF 248 nm Zoom	glass 351 nm Zoom	glass 351 nm no zoom
laser energy	**230 kJ**	**430 kJ**	**645 kJ**
compression energy	160 kJ	280 kJ	360 kJ
gain	**97**	**56**	**35**
absorption	77%	56%	39%
compression absorpt.	87%	70%	55%
max. intensity (PW/cm²)	16.3	28	21.8
$I/I_{2\omega pe\_thresh}$	2.0-2.8	3.8-4.4	4.0-4.7

$$\text{pressure} \sim I_{abs}^{0.7}\lambda^{-0.25}$$

1-D Hydrocode simulations

Simulations predict sufficient energy gains (G) for development of energy application.

G ~100 with a 500kJ KrF laser

→ Fusion Test Facility (FTF)

G ~170 with a 1MJ KrF laser

→ Fusion Power plants

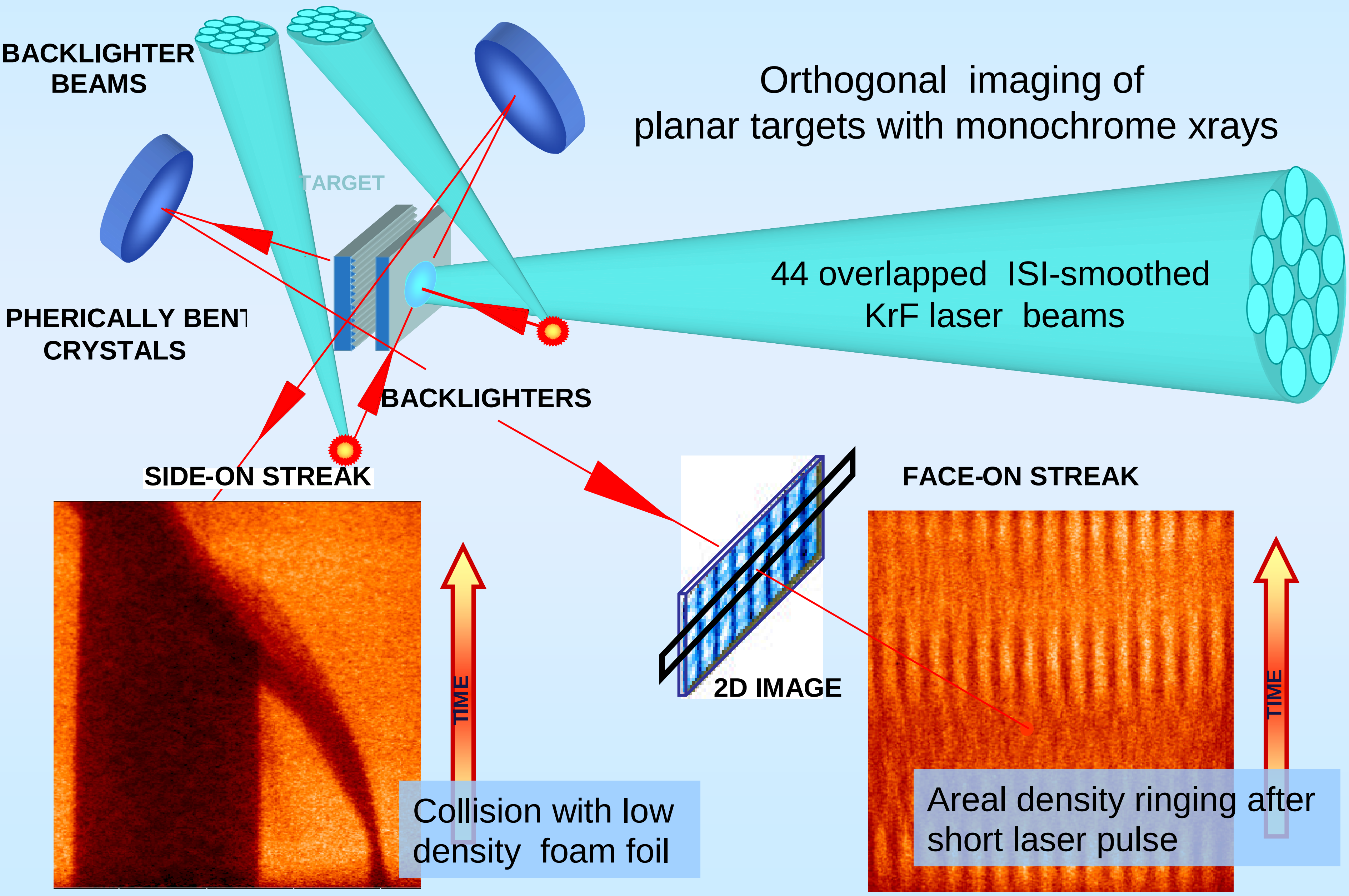
G ~250 with a 2 MJ KrF laser

Desire $G \times \eta \geq 10$ for energy application

η = laser wall plug efficiency $\cong$ 7% for KrF

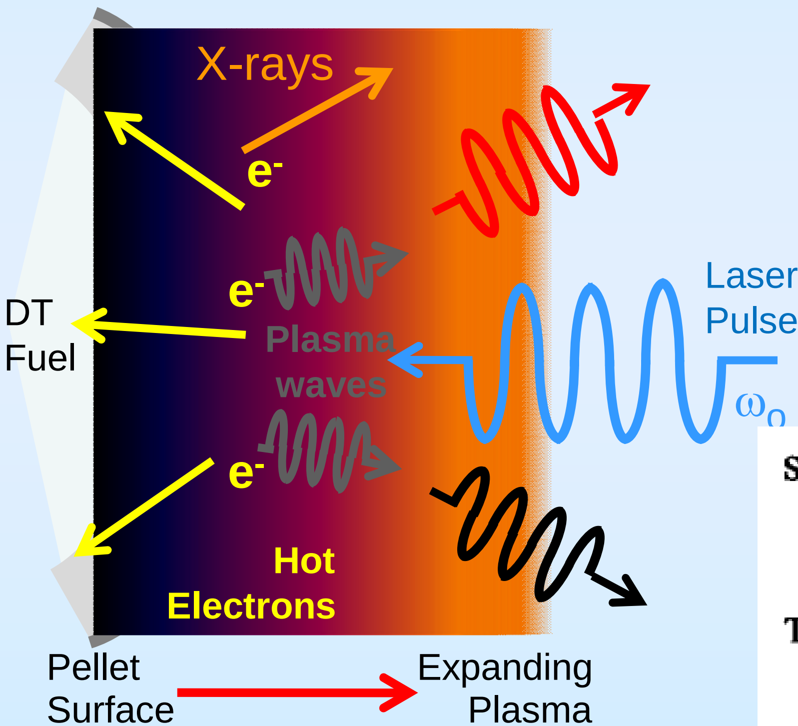
→ need $G \geq 140$

Nike is employed for studies of hydrodynamics and LPI



Laser Plasma Instability limits the maximum intensity

- Can produce high energy electrons that preheat DT fuel
- Can scatters laser beam, reducing drive efficiency



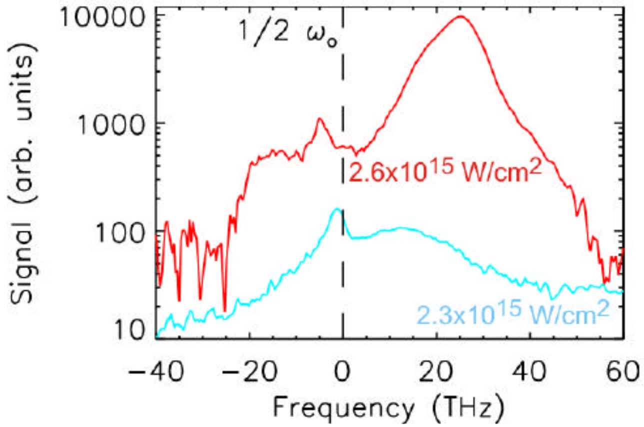
Shorter λ suppresses LPI

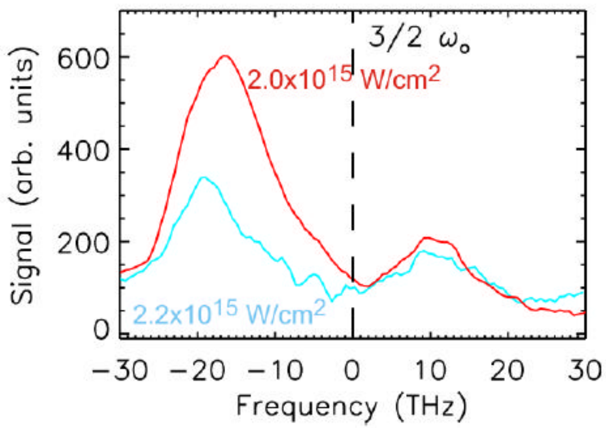
$$(V_{osc}/v_{the})^2 \sim I\lambda^2$$

$N_c/4$ instability thresholds
(single planar beam)

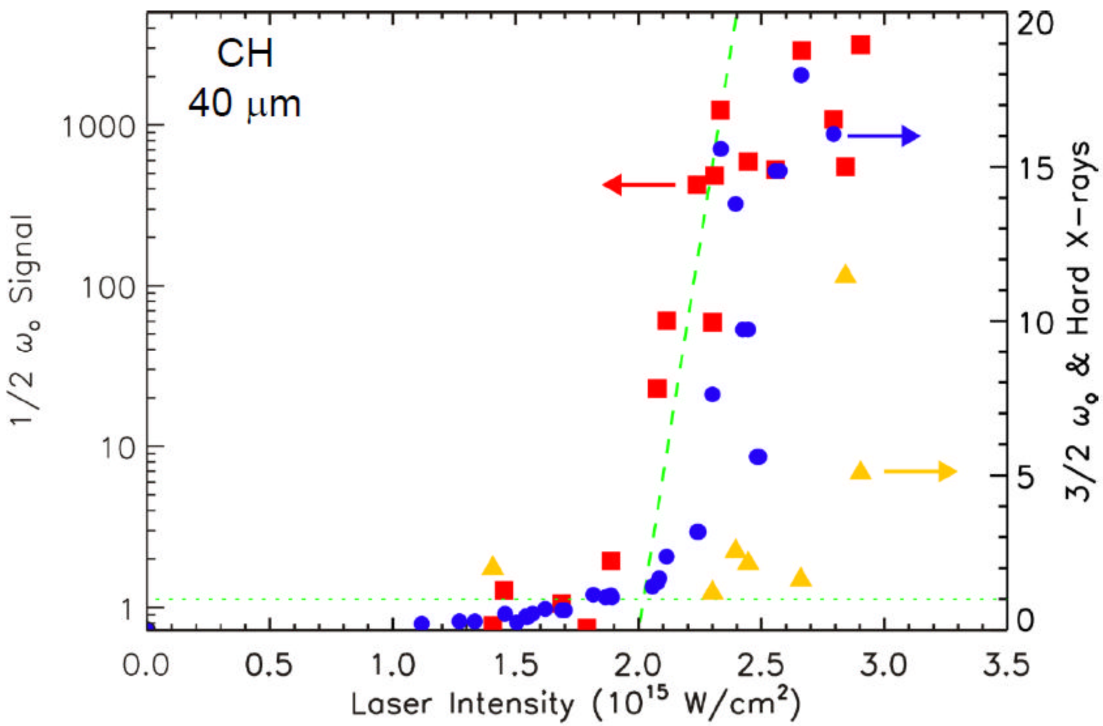
Stimulated Raman scatter ($n \approx 1/4\ n_{cr}$)	$I_t \approx \dfrac{5\times 10^{16}}{L_n^{4/3}(\mu\text{m})\lambda_0^{2/3}(\mu\text{m})}\ \dfrac{\text{W}}{\text{cm}^2}$
Two plasmon decay	$I_t \approx \dfrac{5\times 10^{15}}{L_n(\mu\text{m})\lambda_0(\mu)}\ \theta_{\text{keV}}\ \dfrac{\text{W}}{\text{cm}^2}$

Nike experiments are exploring thresholds for quarter-critical density laser plasma instability



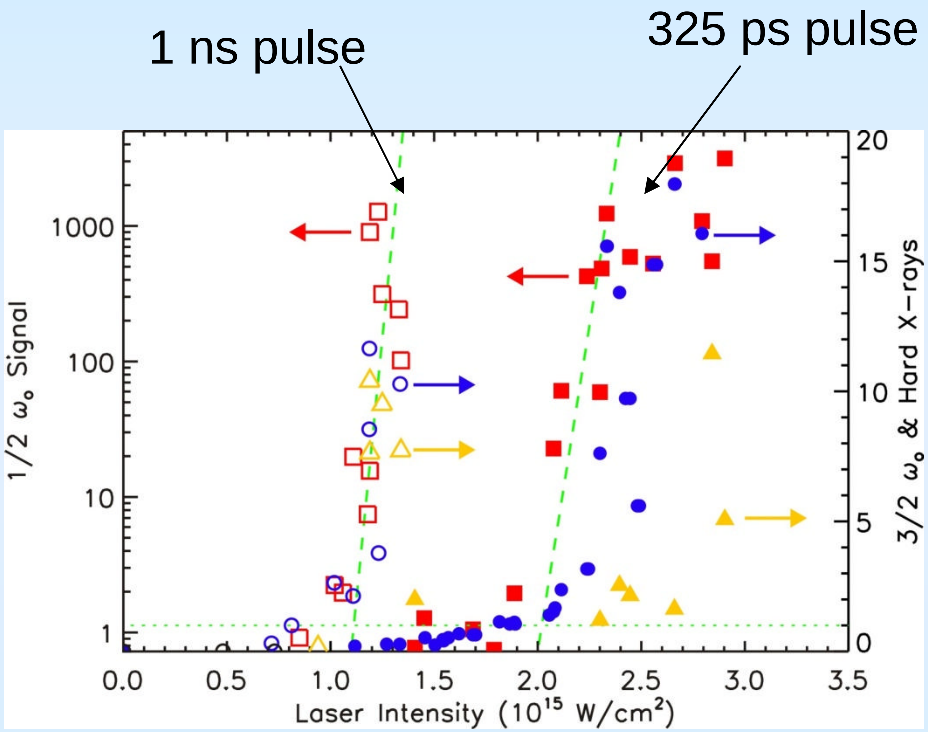


325 ps, ≤1 kJ laser pulses in 40 overlapped beams

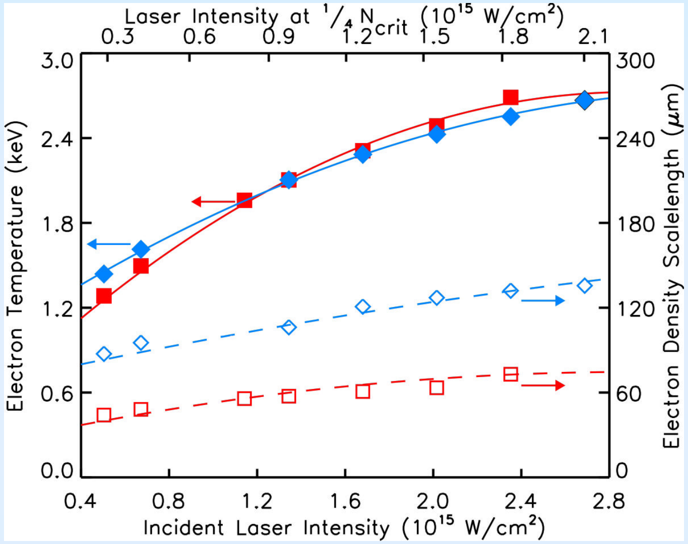


$\omega_0/2$ and x-ray signals give intensity thresholds ~2.0 10^{15} W/cm^2

Longer density scalelength plasma produced by ns laser pulses reduced thresholds (as expected)



I_{th} = 2× 10^{15} W/cm^2 for 325 ps pulse
I_{th} = 1.2×10^{15} W/cm^2 for 1 ns pulse



Computed density scale-lengths @ threshold intensity

~60 μm with 325 ps pulse
~100μm with 1 ns pulse

Similar physics to that observed with λ=351 nm lasers, but quarter critical instability thresholds are higher. (as expected)

KrF, LPI and Direct Drive

- Both theory and experiment indicate use of KrF helps suppress laser plasma instability.
- 1 Thz bandwidth used in current experiments, 3Thz available with Nike.that may help further supress LPI.
- May not be able to operate much above quarter critical instability thresholds during compression stage of SI.
- Can reduce peak intensity during compression by increasing aspect ratio, but limited by hydro-instability.
- **Use of shorter λ and possibly greater Δω are the only unambiguously positive actions to reduce risk from LPI.**
- Preheat from LPI hot elections should not an issue during igniter pulse provided $T_{hot} < 100$ keV per LASNEX simulations by J. Perkins.

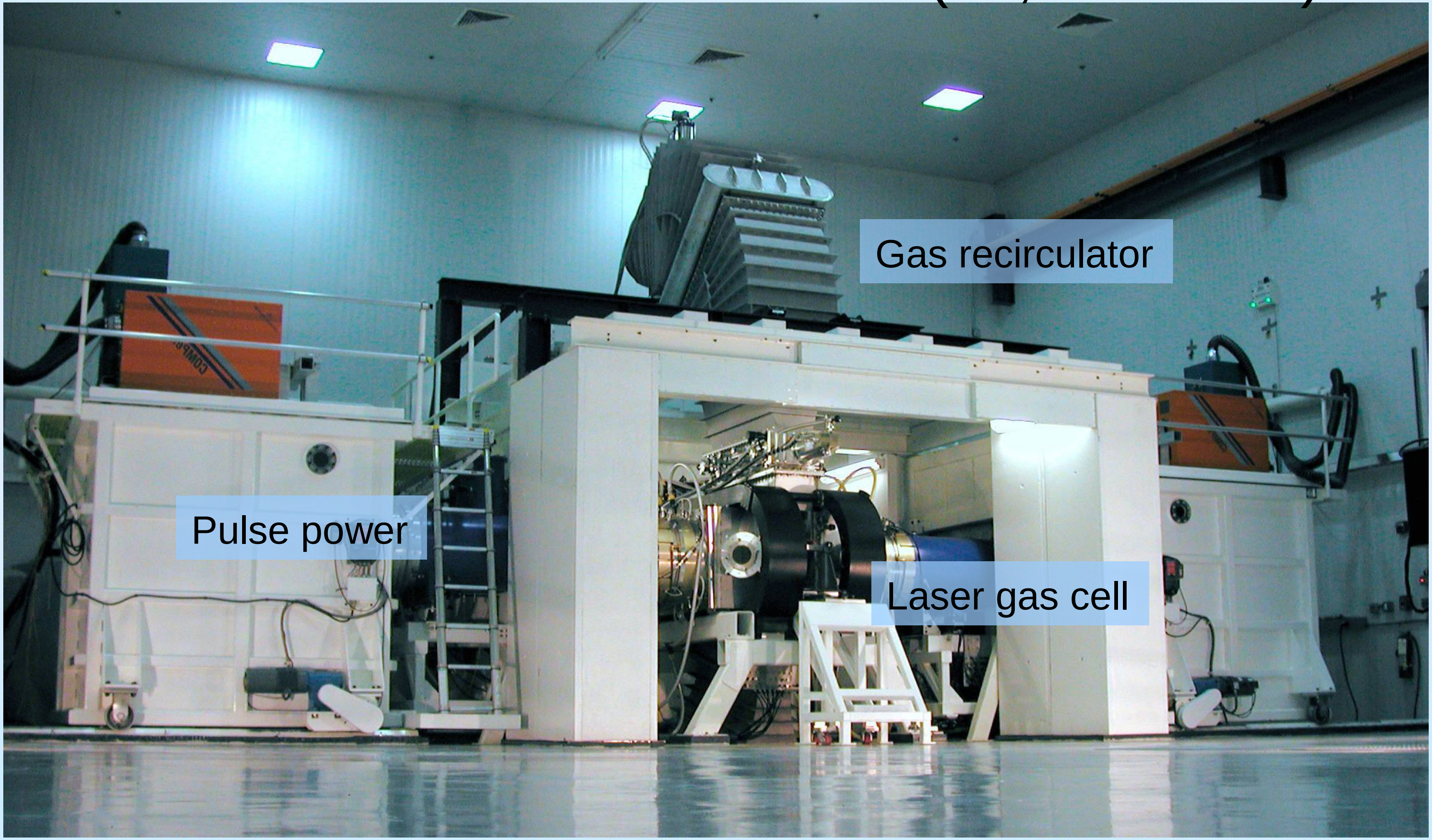
There has been continued progress in high-energy high-repitition rate KrF laser technology

Electra Krypton Fluoride (KrF) Laser

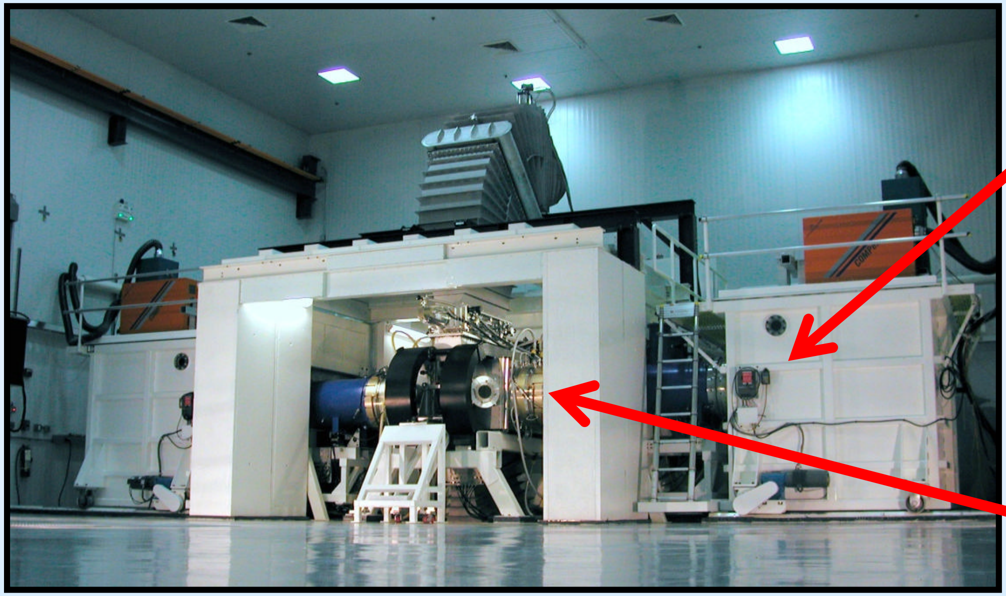
Laser Energy: 300 to 700 Joules

Repetition rate: up to 5 pulses per second

Continuous Runs: 10 hrs at 2.5 Hz (90,000 shots)



Path to much higher durability for Electra identified and developed.



Replace spark-gap switched pulse power with all solid state system.

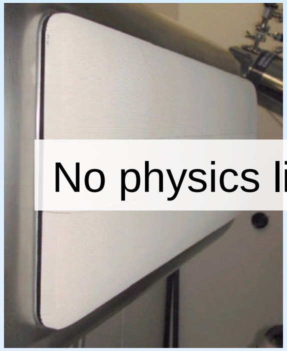
Eliminate "late time" voltage on diode that causes erosion when plasma between anode and cathode close.

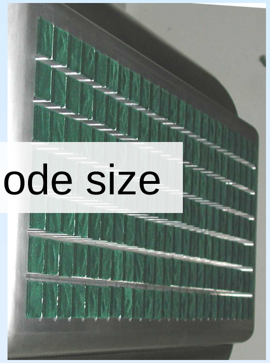
Progress in KrF science and technology

All solid state 10 Hz 180 kV 5KA pulse power system >10^7 shots continuous

Components show > 300 M shots, no failures

Demonstrated two methods to suppress E-beam instability on Nike Main amplifier



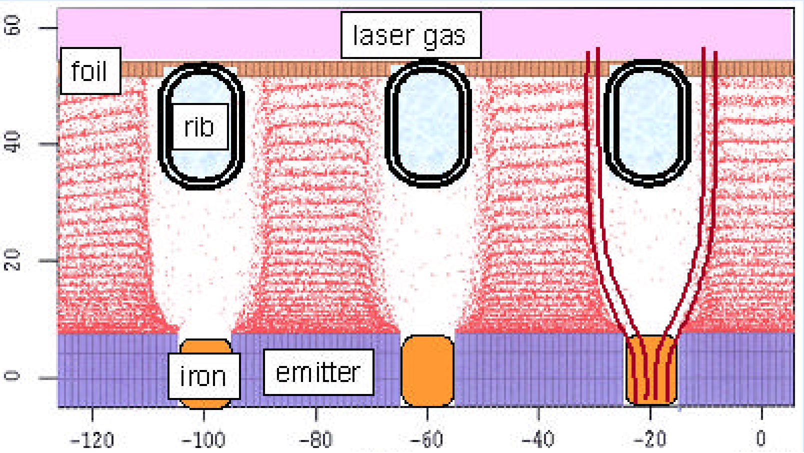


No physics limit on diode size

Ceramic Cathode

Patterned cathode

High efficiency E-beam transport to gas



electron beam guided by tailored magnetic field

>7% wall-plug efficiency looks feasible.

Intrinsic (experiment)	12%
Pulsed power (experiment)	82%
Hibachi @ 800 kV (experiment)	80%
Optical train to target (est)	95%
Ancillaries (est)	95%
Global Efficiency	7.1%

IFE vision

A primary goal of the IFE community should be to develop the technologies for, construct and operate a high repetition rate inertial fusion test facility (FTF) in the decade immediately following NIF ignition.

Adapted from suggestion by Professor Said Abdel-Khalik

See Thursday afternoon presentation by John Sethian: "The need for an Inertial Fusion Engineering Test Facility"

We believe this IFE vision can and should be implemented!

IFE technology development

IFE reactor design

Advances in IFE target physics

Stage 1

~2025

Fusion Test Facility
~250 MW_{th}

- Develop/test fusion materials & components
- Develop/test operation procedures
- Breed tritium fuel
- DEMO net power production (~50 MW_e)

Stage II

Stage III

Commercial fusion power to the grid

Prototype GW_e Power Plant(s)

Summary

- Shock ignited direct drive continues to look very attractive for the energy application.
- Both simulations and experiments indicate KrF light significantly improves the laser-target interaction physics.
- Good progress in the S&T of E-beam pumped KrF towards the goal of obtaining the high system durability needed for IFE.

References

Laser Inertial fusion energy technology

J.D. Sethian et al, “The science and technologies for fusion energy with lasers and direct drive targets,” Proceedings, 23rd Symposium on Fusion Engineering. *IEEE Transactions on Plasma Science*. Vol. 38, NO. 4, 690 (2010).

High Average Power :Laser Program   http://aries.ucsd.edu/HAPL

Shock Ignited direct drive designs

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Fusion Test Facility (FTF) utilizing a KrF laser

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